Methodology for Composite Durability Assessment

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Objective

The goal of the AIM-C program

(1) Accelerate the insertion of new materials and processes

(2) Evaluate the effects of material, processing, and design on the performance of composite structures

Our objective is to add the capability to analyze

- **Environmental effects**
  - Temperature
  - Moisture
- **Durability**
  - Creep Loading
  - Fatigue Loading
  - Residual Strength

Approach

Our approach is based on the following methods

1. Accelerated Testing Methodology

- Accelerated durability assessment
- Evaluate effects of temperature and loading on strength

2. Strain Invariant Failure Theory (SIFT)

- Relate fiber and matrix to composite structures
- Significant reduction in required durability tests
- Simplifies effects of moisture and temperature

Typical Approach to Durability

Fatigue, creep, or static loading

Cycles to failure

~~Time to failure~~ ⇒ ignored

Temperature ⇒ fixed

Moisture ⇒ fixed

Ply orientations ⇒ fixed

Applied stress state ⇒ fixed

S-N Curve Approach

applicable only to limited ply orientations, loads, temperatures, etc.

"Static" Failure Analysis

Geometry

optimized for static strength and later checked for durability

Durability data applicable only to intended applications

Our Approach to the Durability of Composites

Fatigue, creep, or static loading

Cycles to failure

Time to failure

Temperature

Moisture

Accelerated Testing Methodology

applicable to wide ranges of loads, temperatures, etc.

Ply orientations

Applied stress state

Geometry

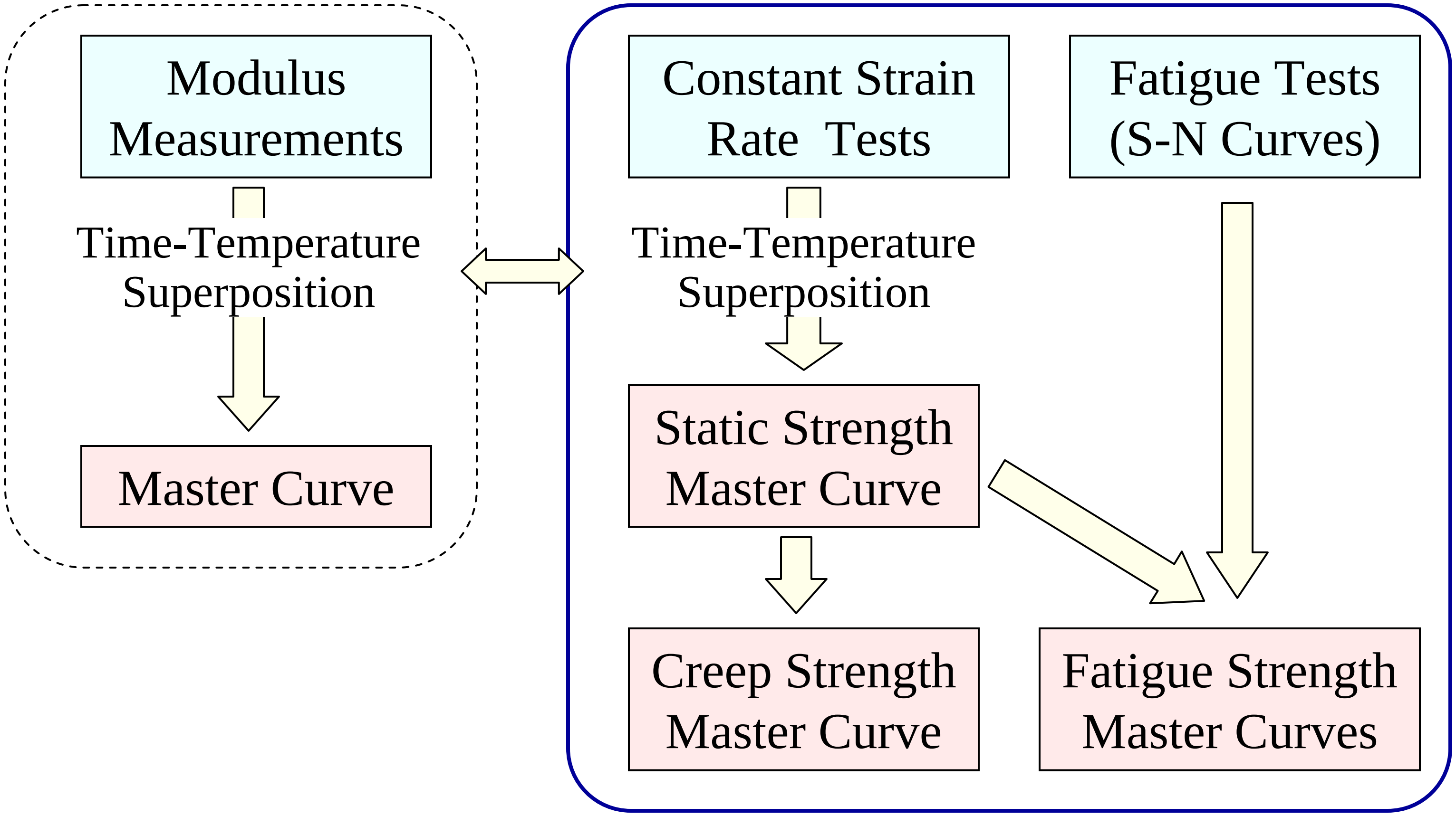
Failure Analysis

SIFT modified for time- and temperature-dependence

Durability data applicable to wide ranges of applications

Accelerated Testing Methodology

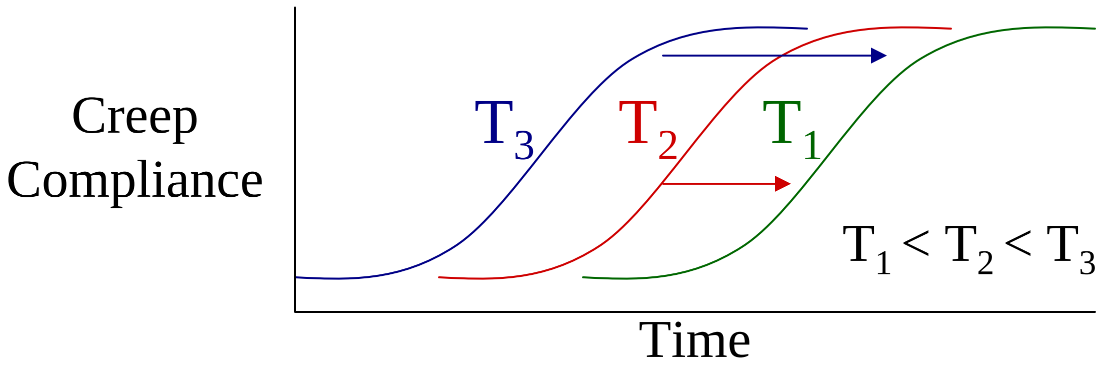
Series of tests at elevated temperature



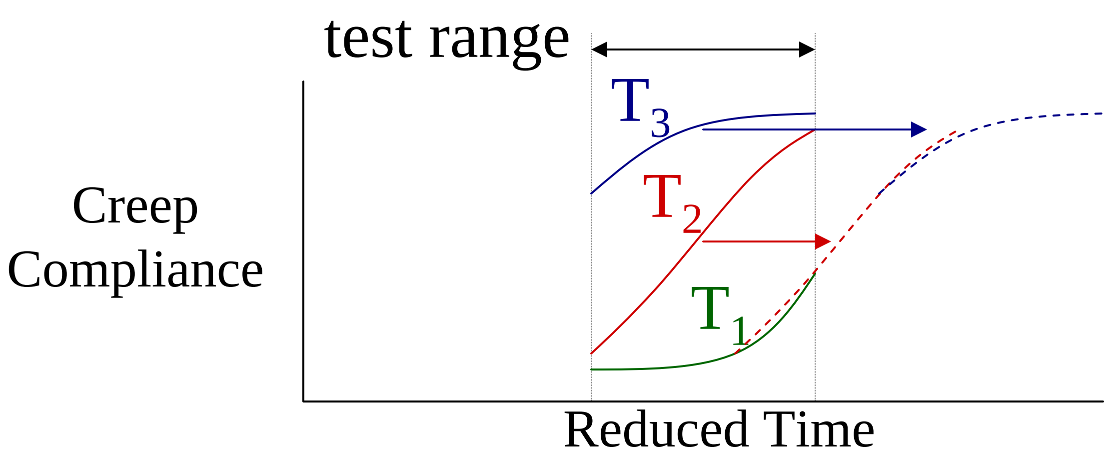
Predictions for wide ranges of temperature and time to failure

Time-Temperature Superposition Principle

Assumption: Same curve for any temperature = Master Curve



All curves can be superposed by horizontal shift

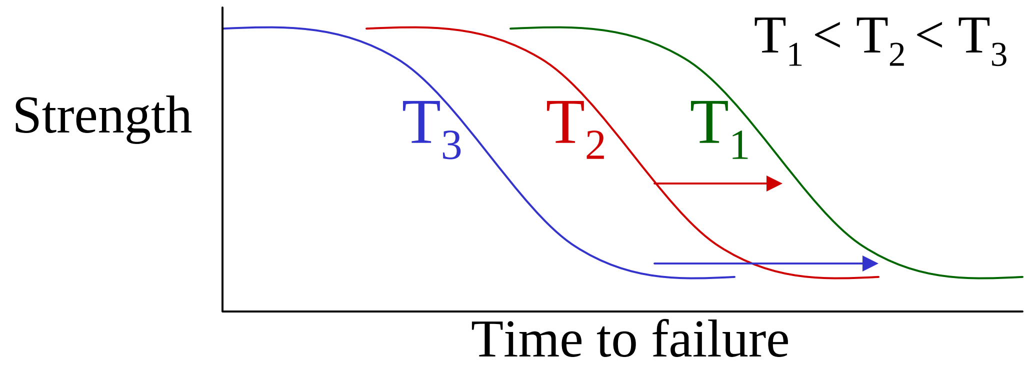


Master curve can be determined from curves at different temperatures

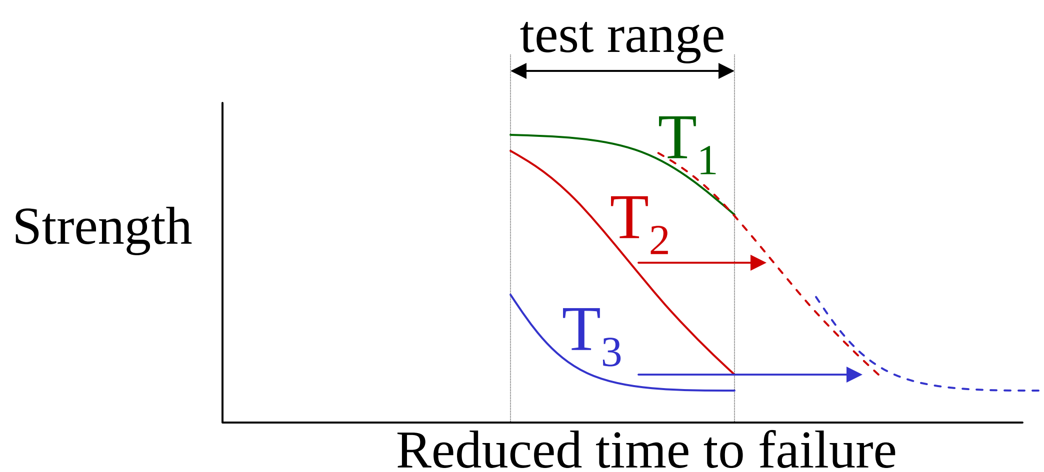
Well established principle for viscoelastic materials

Time-Temperature Superposition on Strength

Assumption: Same curve for any temperature = Master Curve



All curves can be superposed by horizontal shift

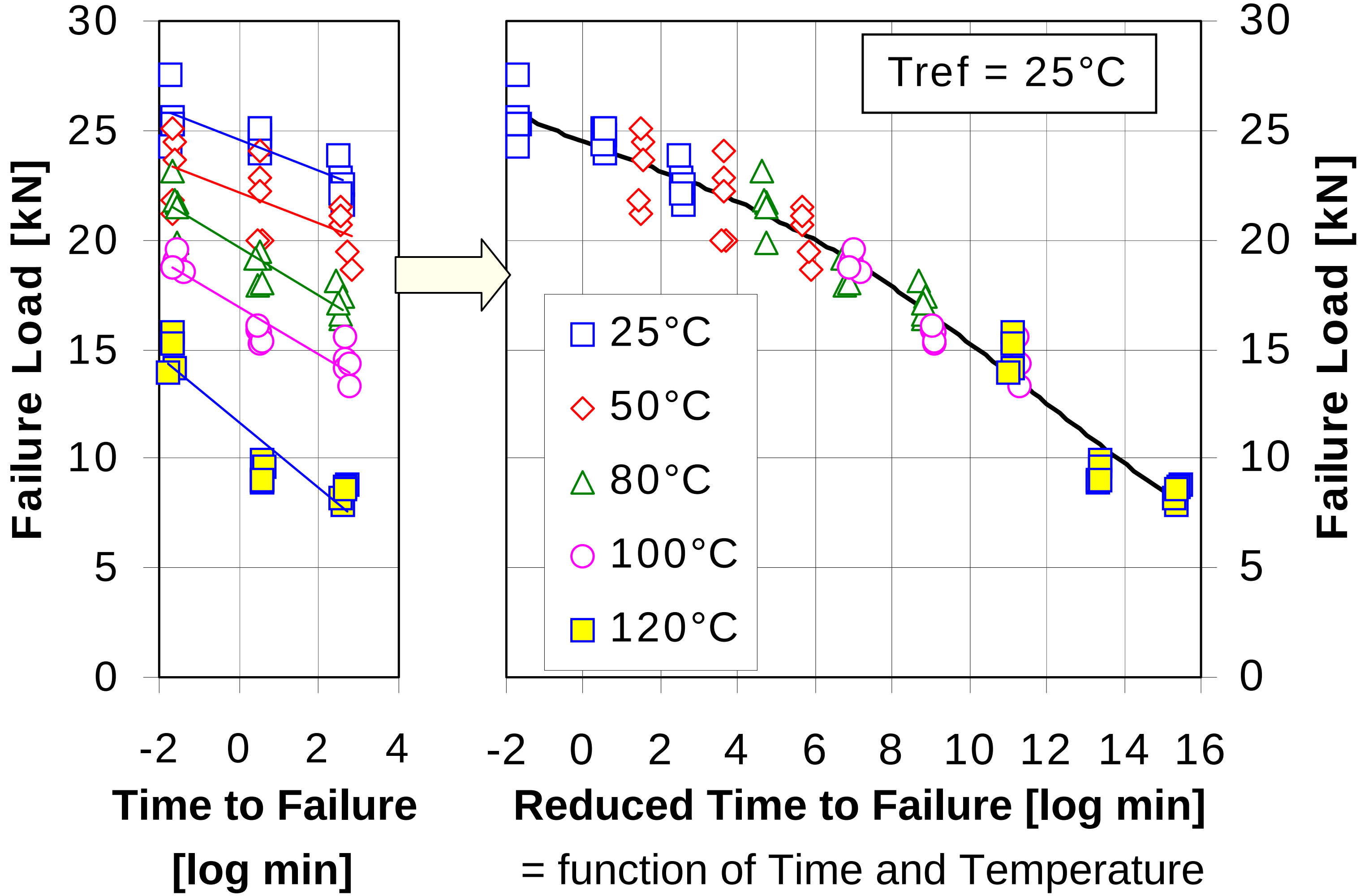


Master curve can be determined from curves at different temperatures

Related to the viscoelastic fracture and not the chemical degradation

Master Curve of Static Strength

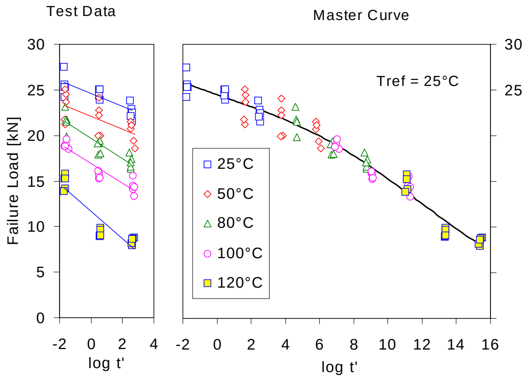
CFRP Bolted Joint Tensile Test (Miyano)



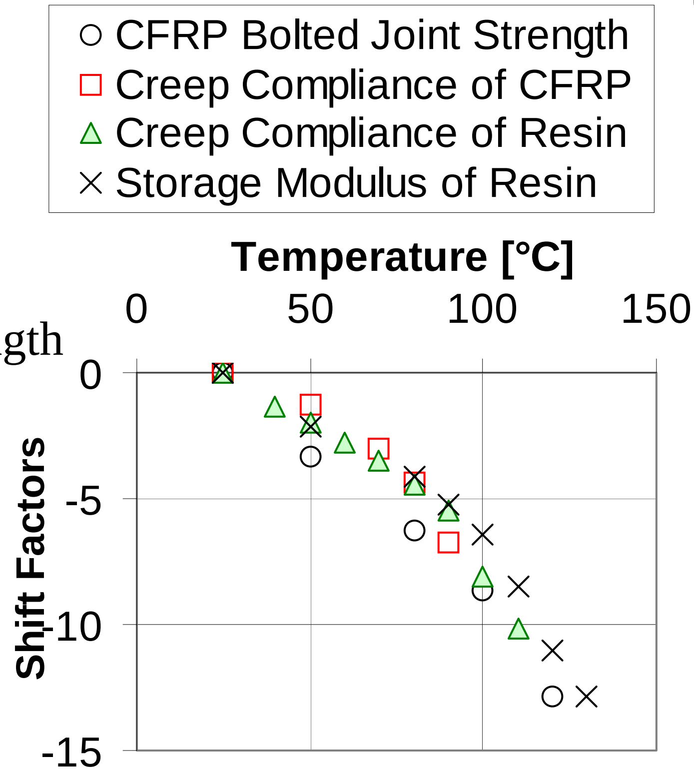
= function of Time and Temperature

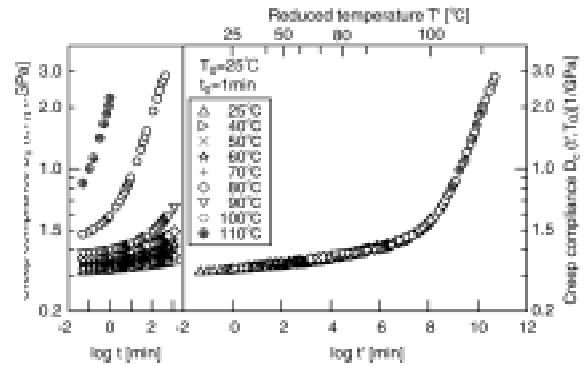
$\log t_f' = \log t_f + a_T$

Time Temperature Shift Factors

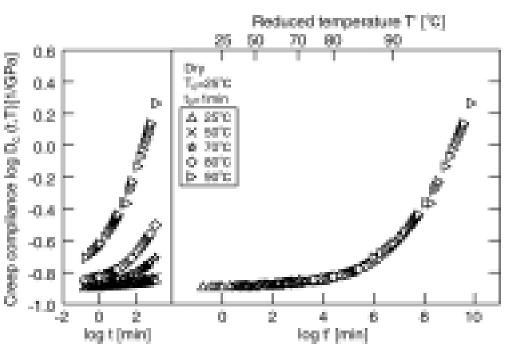


CFRP Bolted Joint Strength

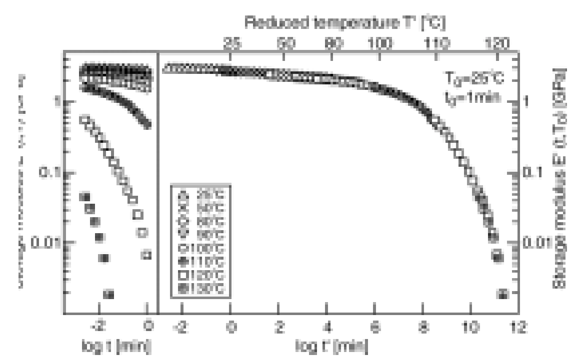




Creep Compliance of Resin



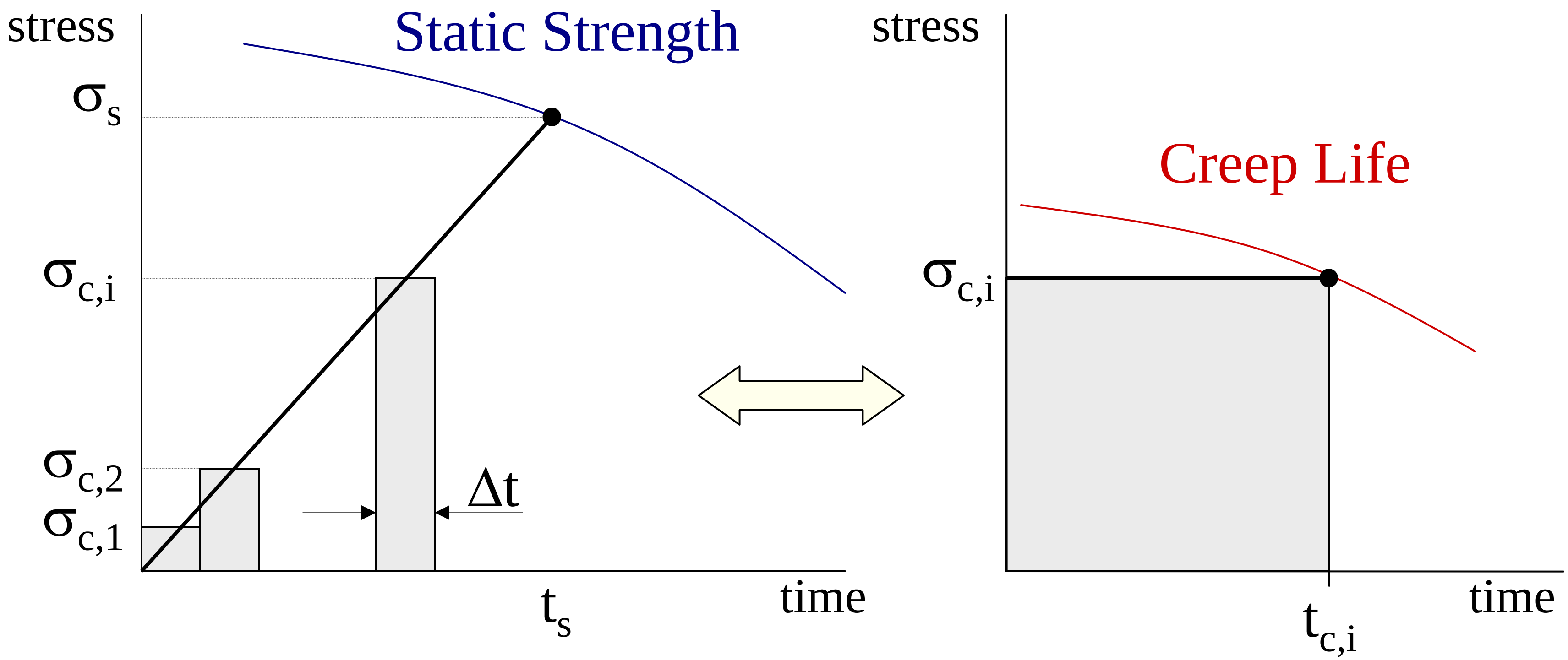
Creep Compliance of CFRP



Storage Modulus of Resin

Same shift factors for various cases with common resin system

Relate Static Strength and Creep Life

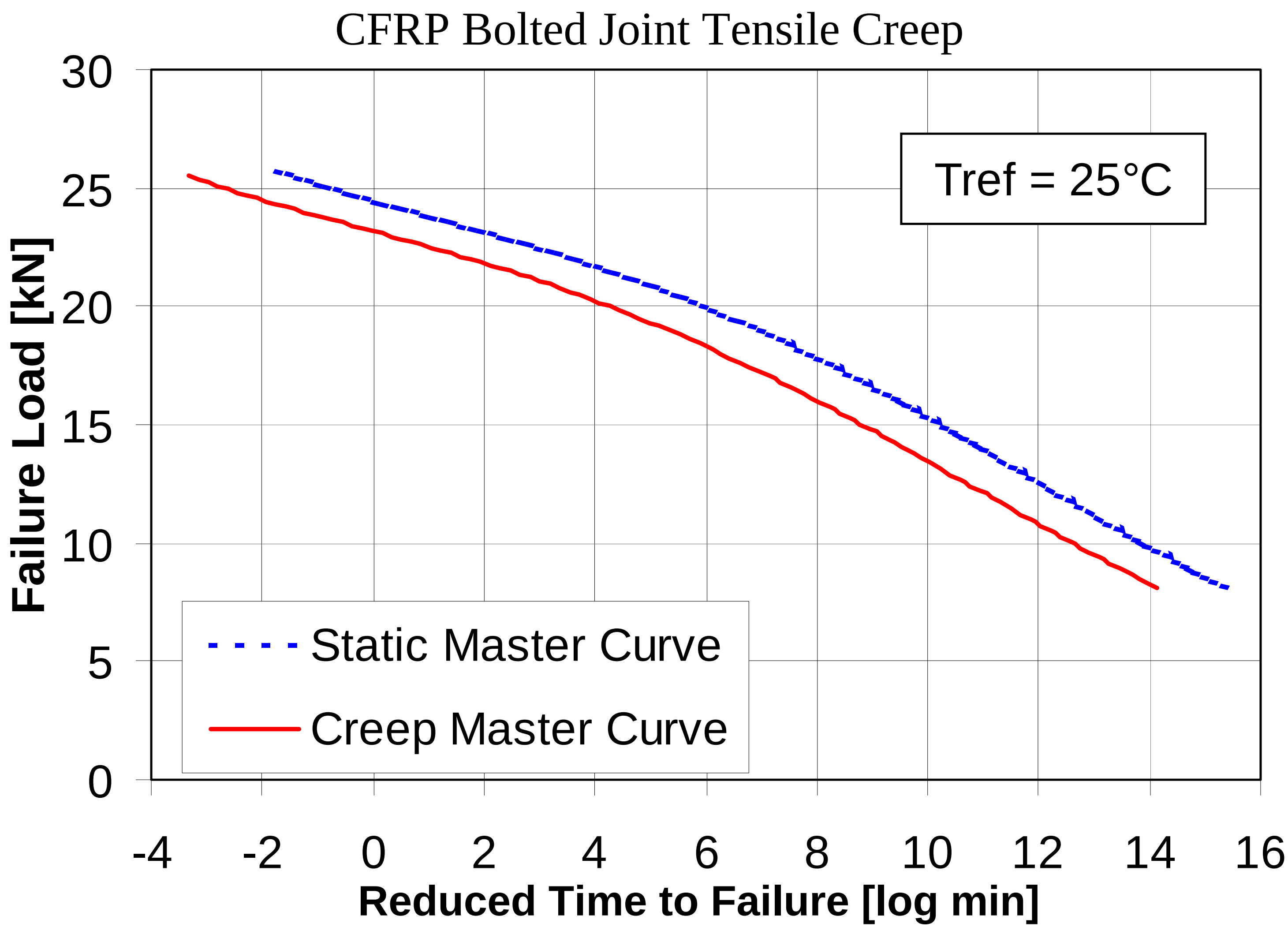


Linear Cumulative Damage Law with respect to time

$$\frac{\Delta t}{t_{c,1}} + \frac{\Delta t}{t_{c,2}} + \ldots + \frac{\Delta t}{t_{c,n}} = 1$$

Simple relation between creep life and static strength

Master Curve of Creep Life

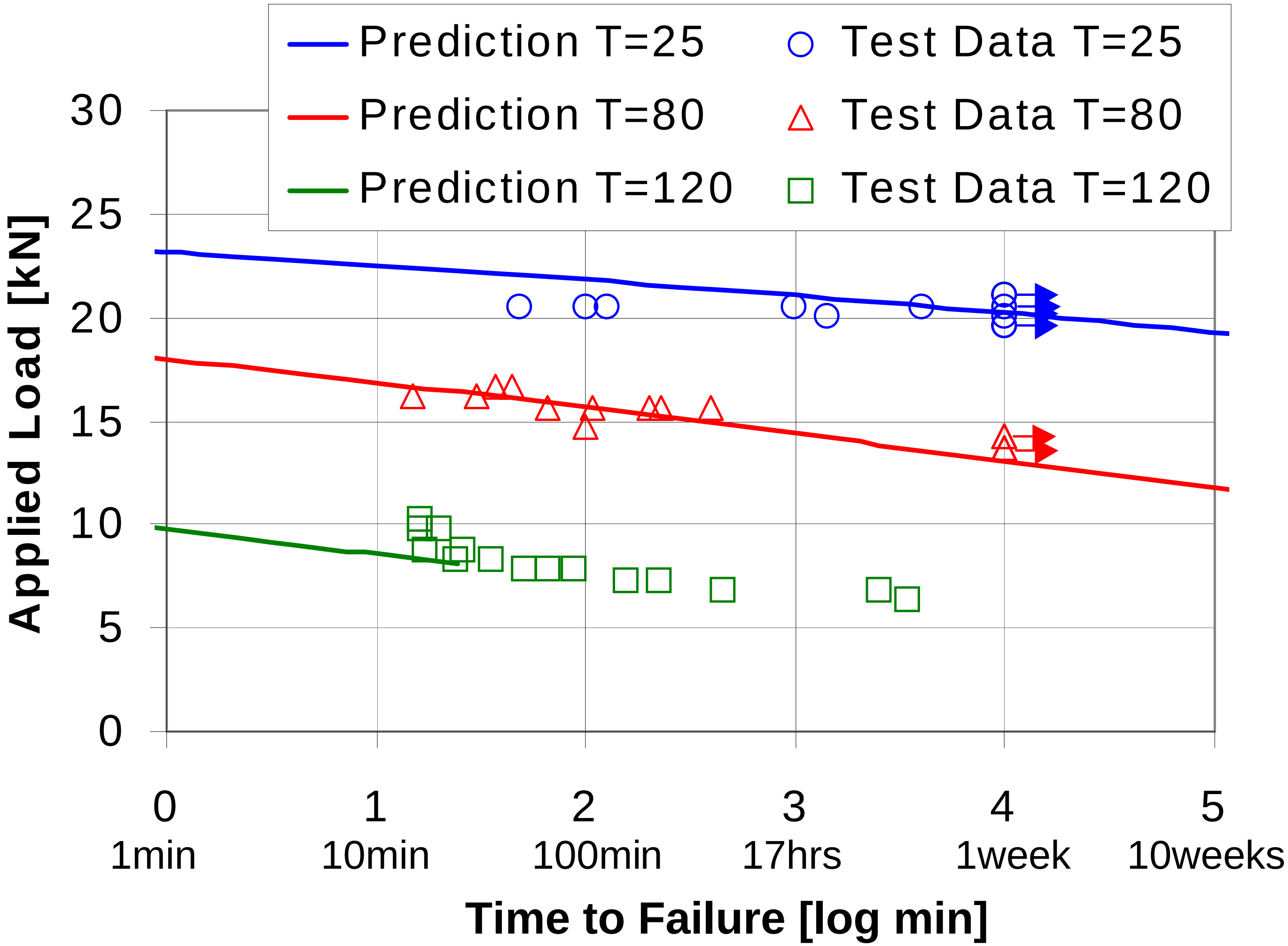


Time to failure at 25^{o}C 1min 100min 1wk 2yrs 190yrs

Time to failure at 50^{o}C 1min 100min 1wk 2yrs 190yrs

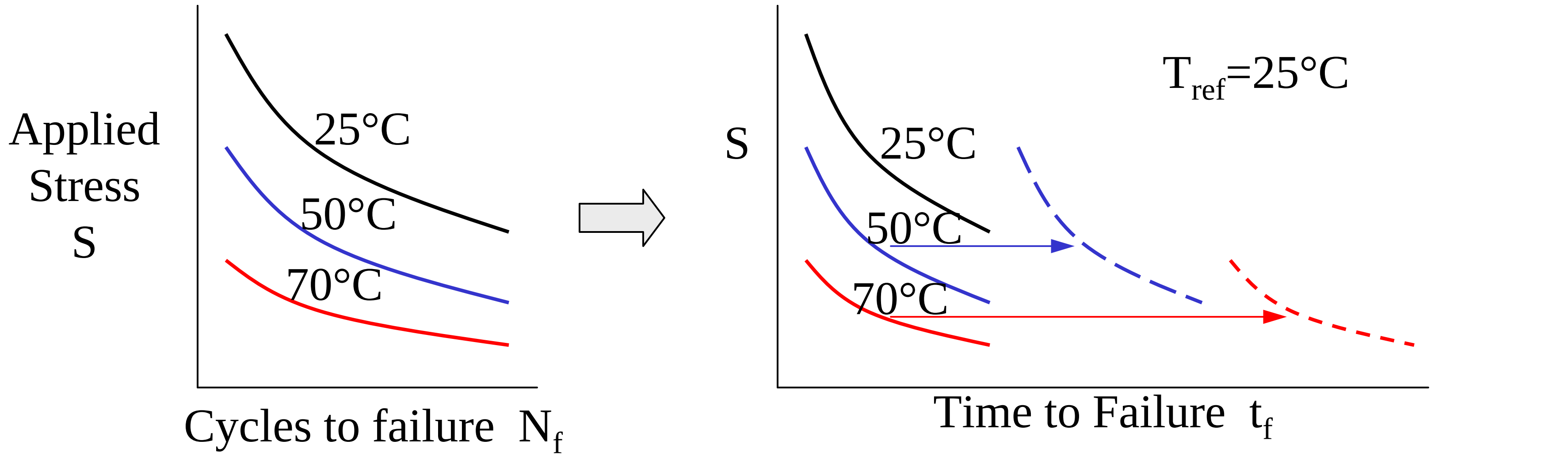
Creep Predictions and Measurements

CFRP Bolted Joint Tensile Creep Test (Miyano)

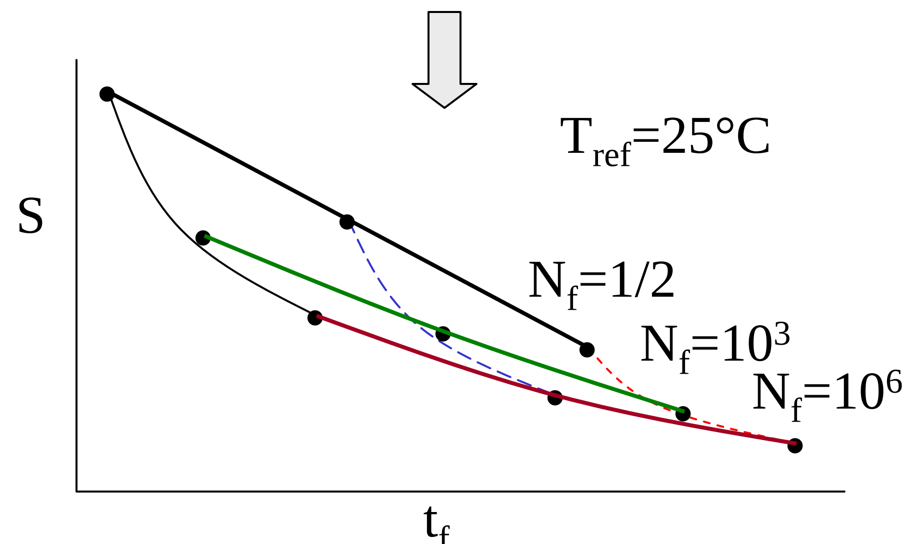


Creep life is predicted from series of constant-strain-rate tests

Creating the Fatigue Master Curves

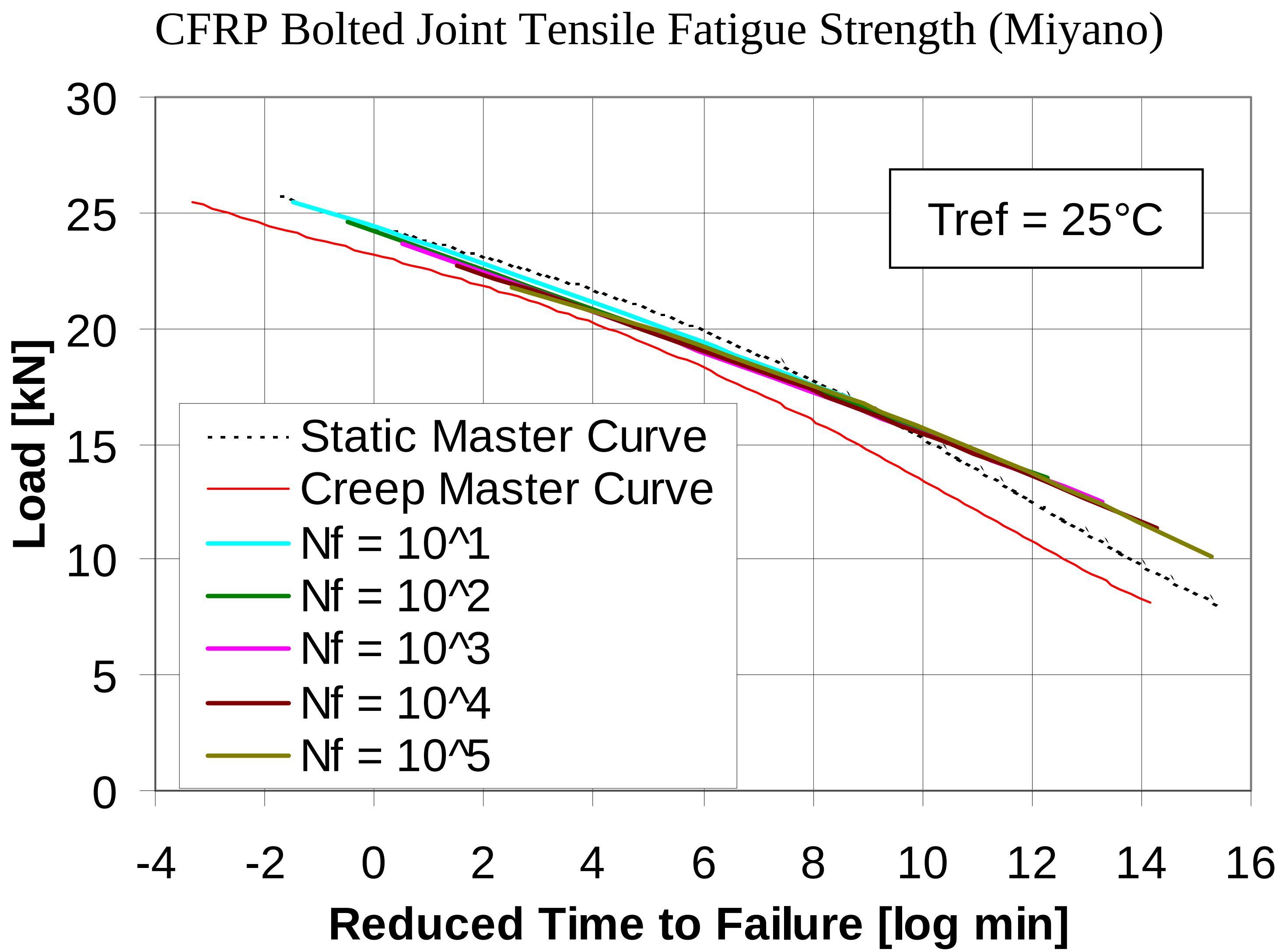


1. Calculate time to failure
   $t_f = N_f / 60f$
2. Shift S-t_f curves
3. Connect constant N_f



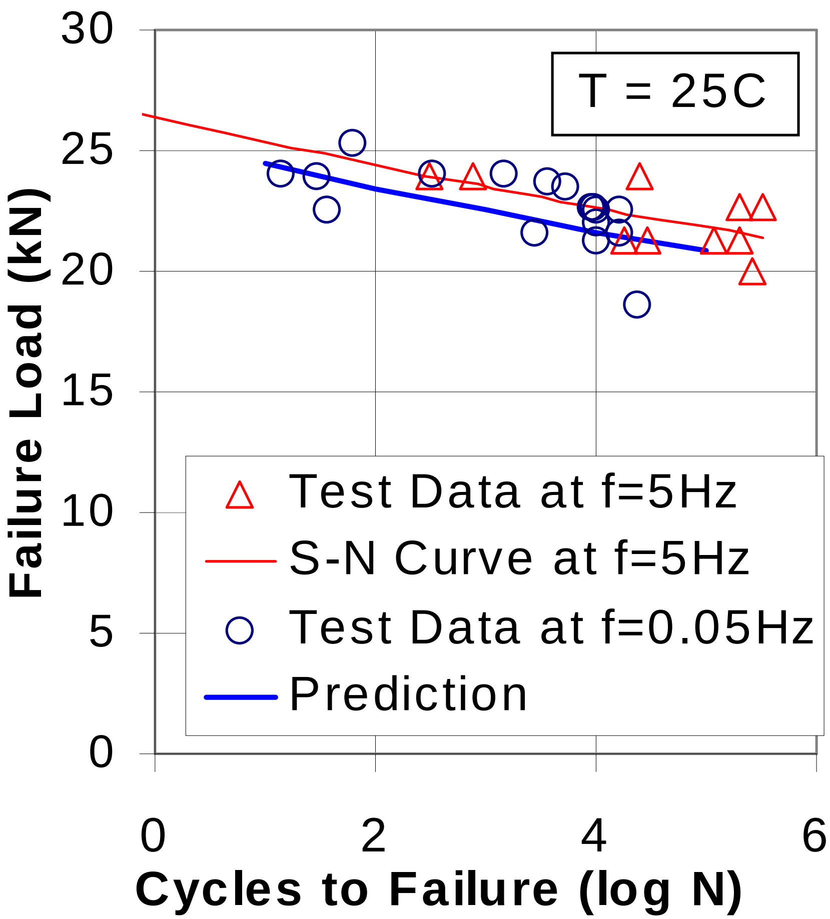
Predict long-term fatigue from S-N curves at elevated temperatures

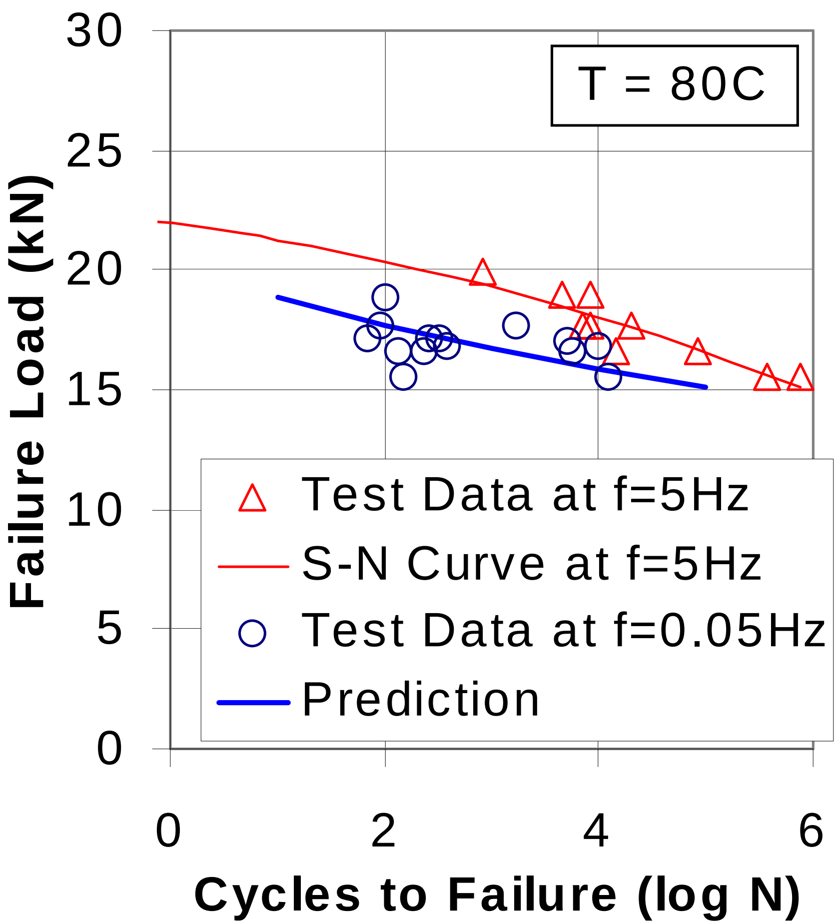
Fatigue Master Curves



Fatigue Predictions and Measurements

CFRP Bolted Joint Fatigue Strength - Frequency Effect (Miyano)



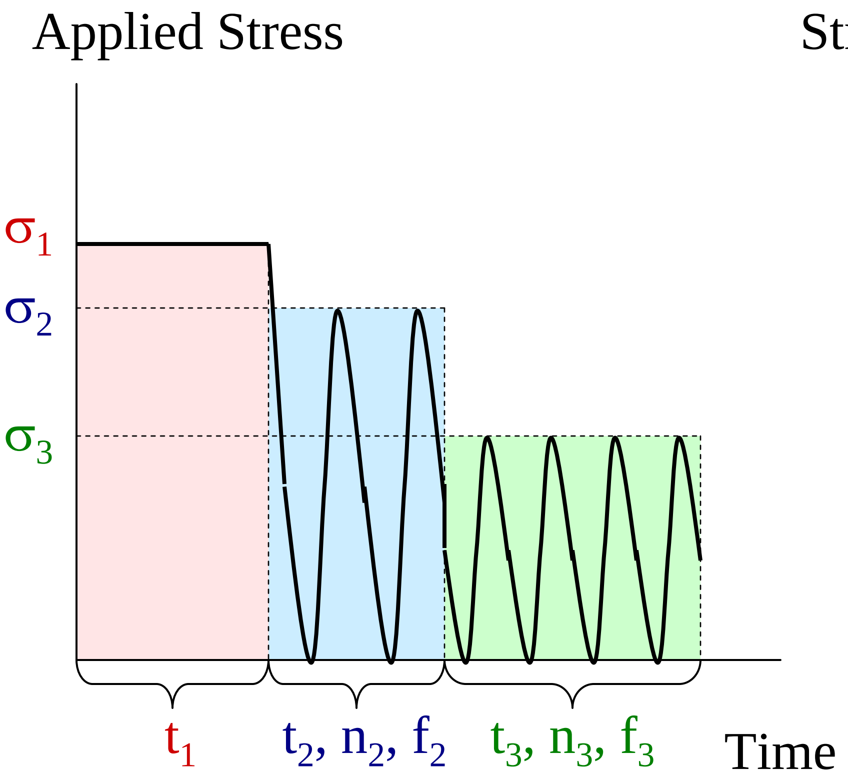


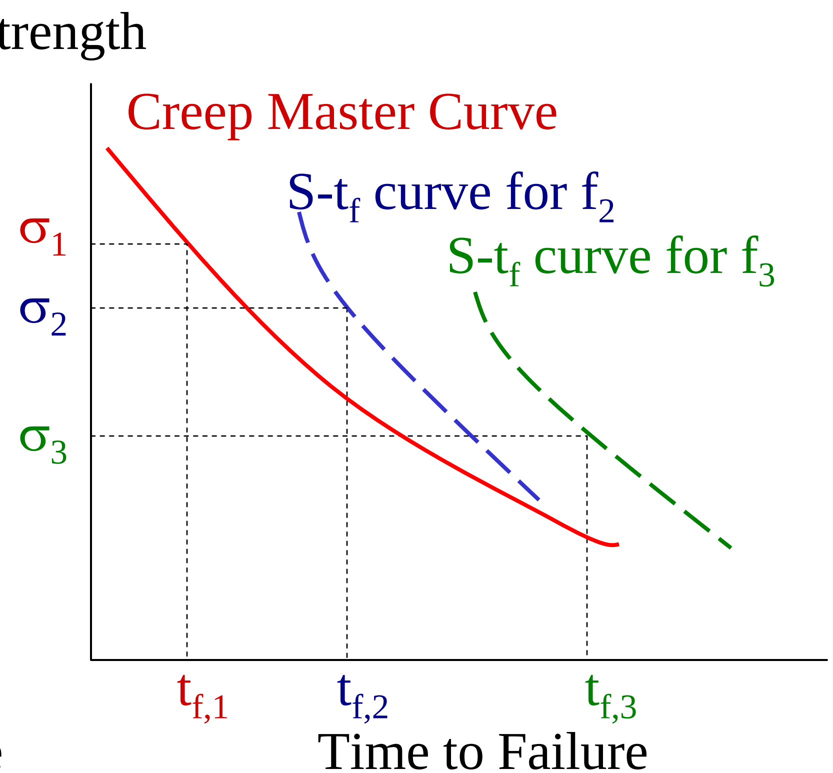
Frequency effect on fatigue strength is correctly predicted

Cumulative Damage Law

Miner's Rule accumulates damage due to load **cycles**

Robinson's Rule accumulates damage due to loading **time**





Robinson's Rule: $t_1 / t_{f,1} + t_2 / t_{f,2} + t_3 / t_{f,3} + \ldots = 1$

Limitation of the Methodology

Current limitations of the Accelerated Testing Methodology are

• Series of constant-strain-rate tests and fatigue tests must be performed for each ply orientations and test configurations

• Tests must be performed for both dry and wet conditions

• Links between the resin and composite properties are observed but cannot be explained

Why Combine with SIFT

SIFT will provide keys to

• Predict the strength of complex structures from basic properties

• Reduce the numbers of durability tests

• Link the resin properties to composite properties

• Effect of moisture and other degradations are easier to analyze at the resin level

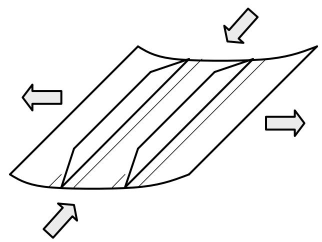
Strain Invariant Failure Theory

Detailed 3D FEA of complex structures
combined with simple strain-based failure criterion

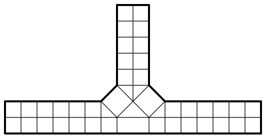
Design parameters

- Ply orientations
- Material
- Complex geometry

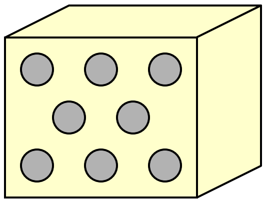
3-D Finite element analysis



Global



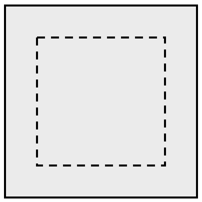
Local



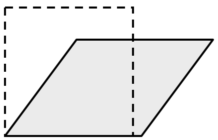
Micro-mechanic

Failure Criteria

3 Strain invariants



dilatational



distortional

Prediction

Prediction of failure

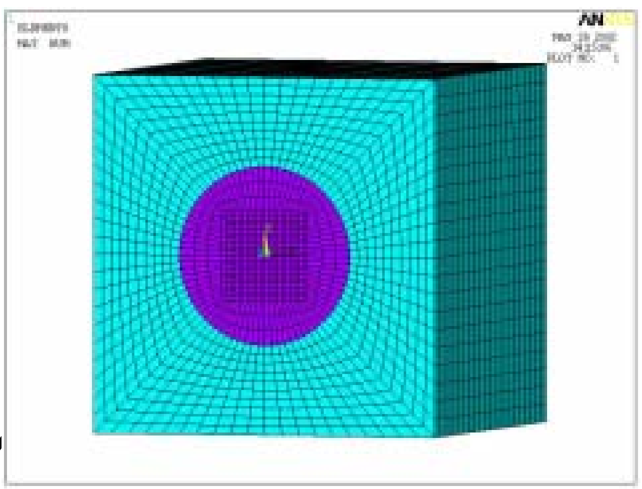
Micro-Mechanical Analysis in SIFT

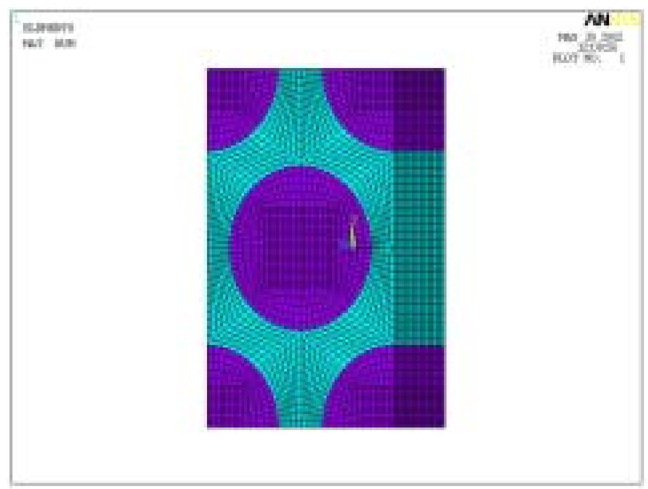
SIFT evaluates local strain states of fiber and matrix through extensive Micromechanical analysis

Advantages for our durability analysis

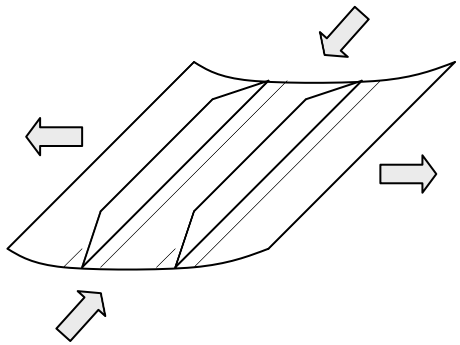
- Significant reduction of the required durability tests
- Easier to analyze the **temperature** and **moisture** effects of resin
- Generate ply properties: A bottom up tool

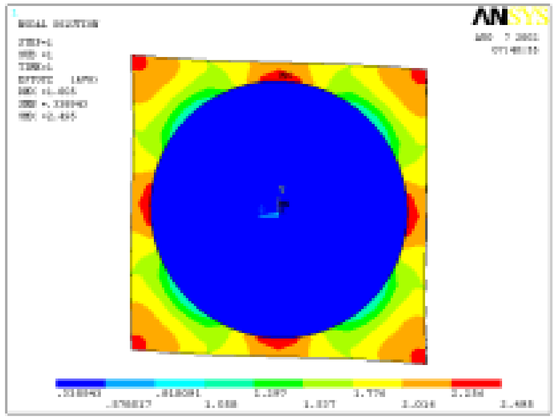
Example of the Square Array Model and Hexagonal Array Model (Ha)

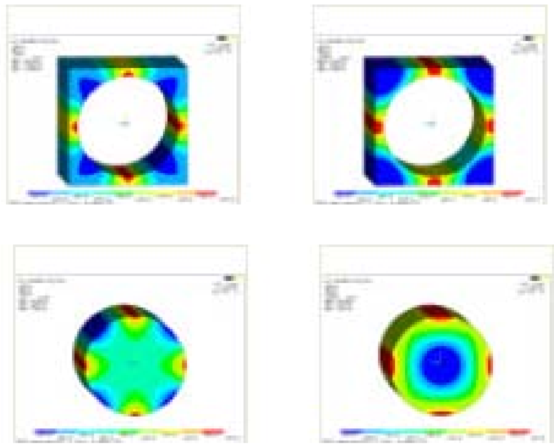




SIFT Analysis Procedure







3-D macro strains
due to mechanical
and thermal load

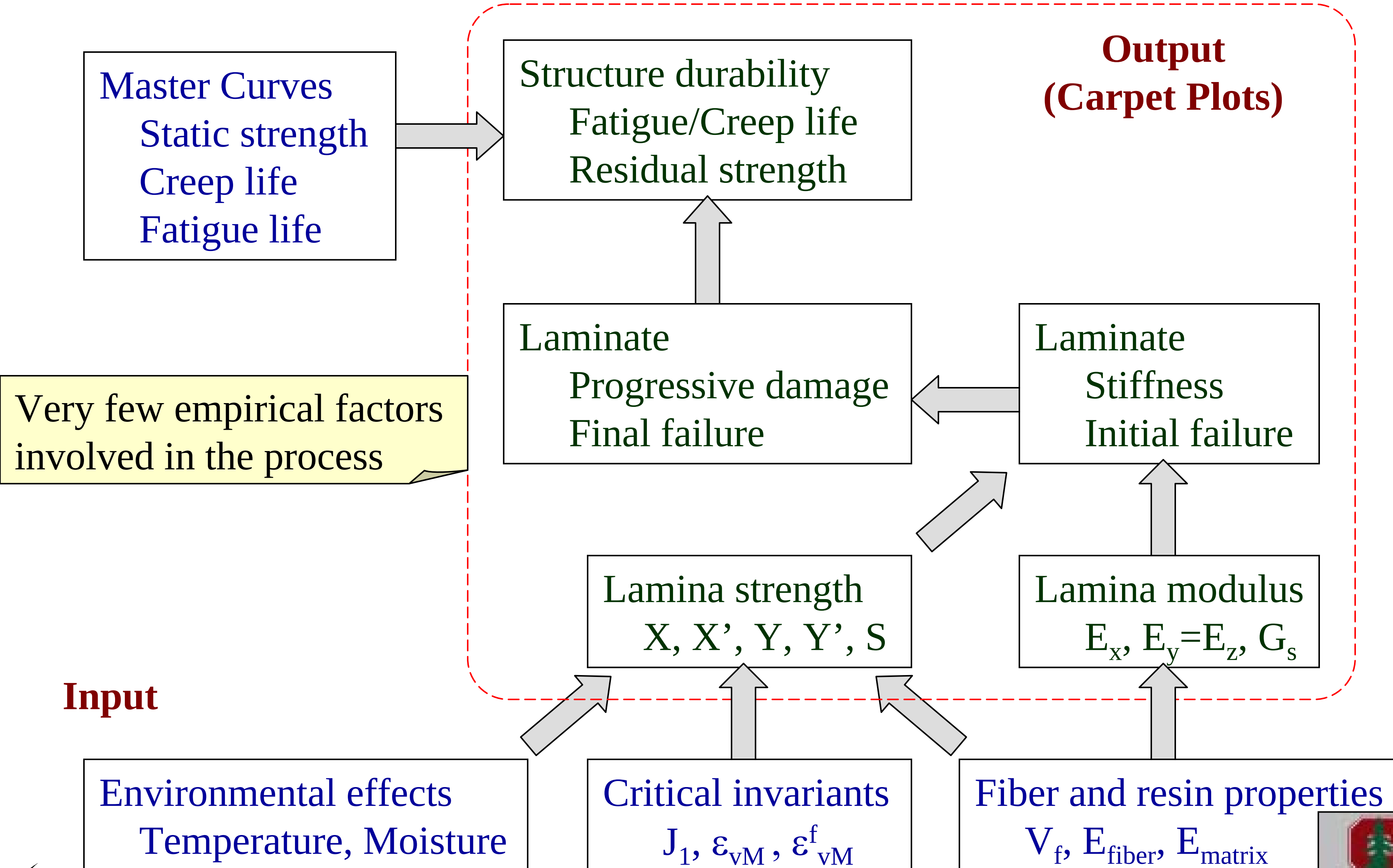
3-D micro strains
at various locations
in the fiber and resin
+
Micro thermal strains
due to CTE mismatch
of fiber and resin

Strain invariants
in the resin
and in the fiber

compare

Critical invariants

Electronic Carpet Plot

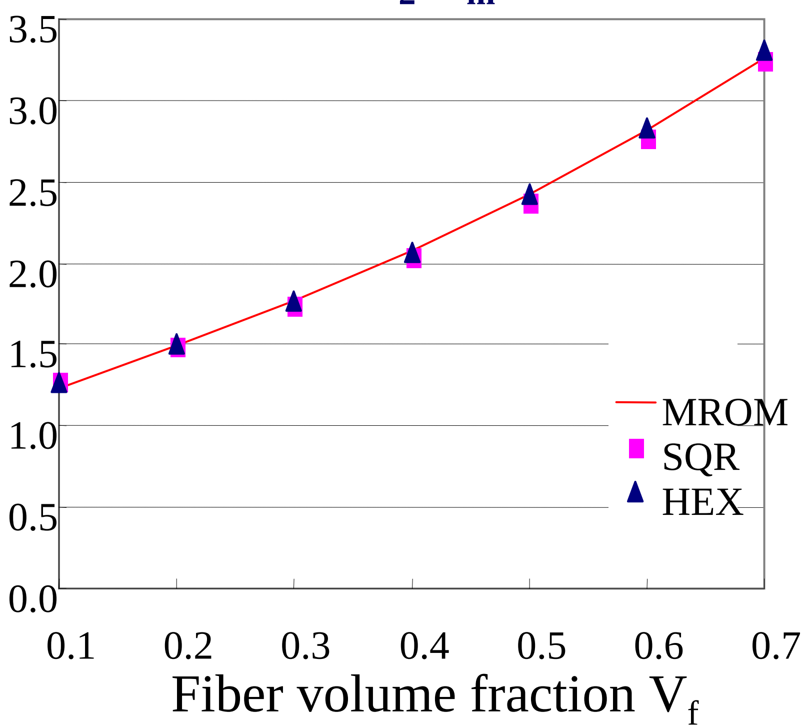


Predicted Ply Properties

- Material: IM7/Epoxy, E_f/E_m=92
- Square and Hexagonal Micromechanics Model
- Compared with the Modified Rule of Mixture

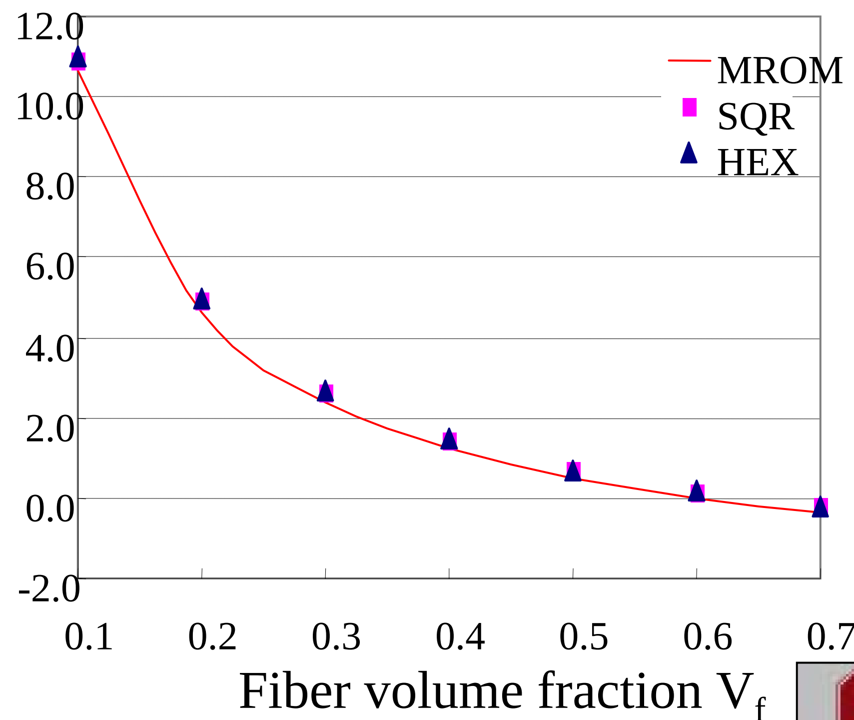
Transverse modulus / Resin modulus

E_2/E_m



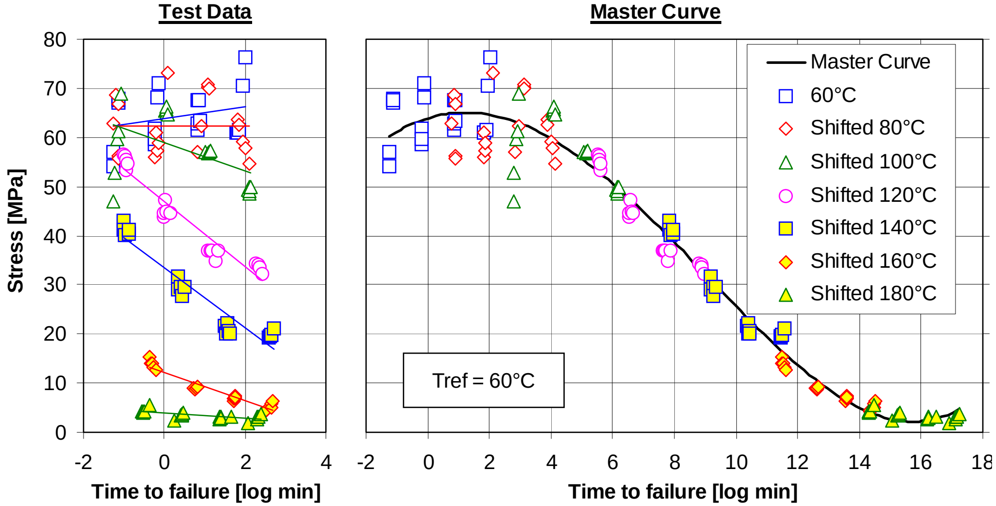
Longitudinal CTE / Fiber CTE

α_1/α_f

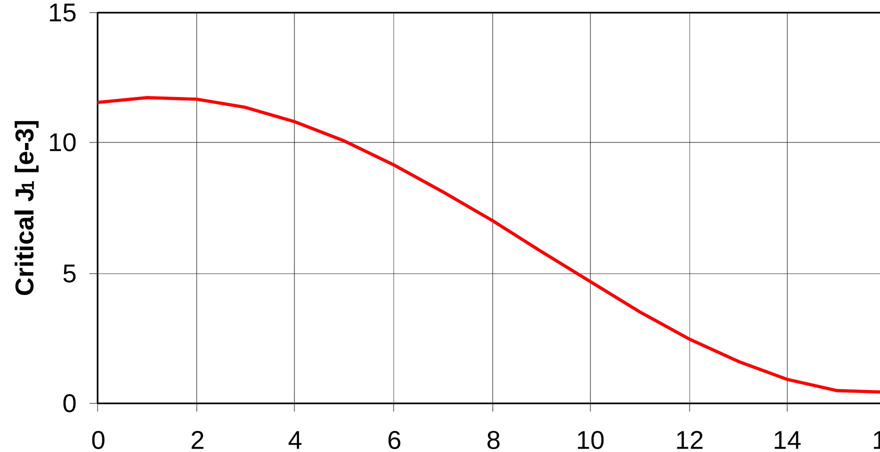


Ply Strength Predicted from Resin Properties

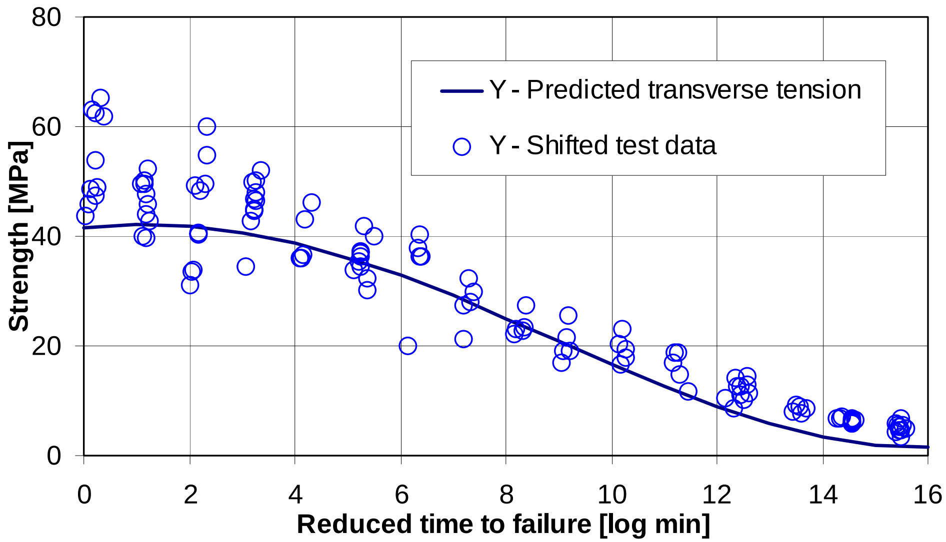
Test data and master curve of resin tensile strength (828resin)



Master curve of critical J_1



Reduced time to failure [log min]
= function of time and temperature

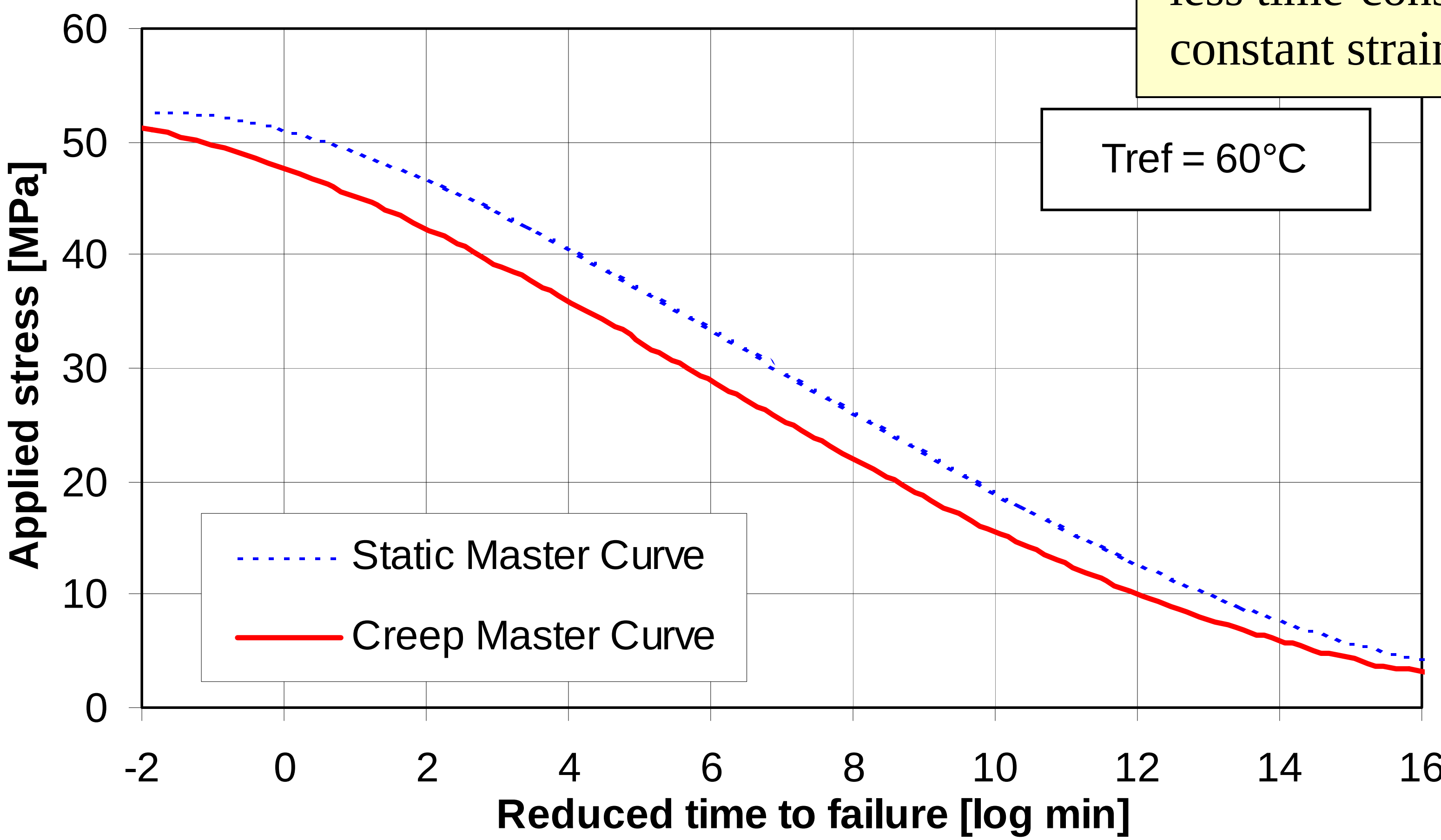


Master curve of transverse tensile strength of composite laminates (T300/828)
(with test data for comparison)

Predicted Creep Life

Based on linear cumulative damage law
and time-dependence of strength

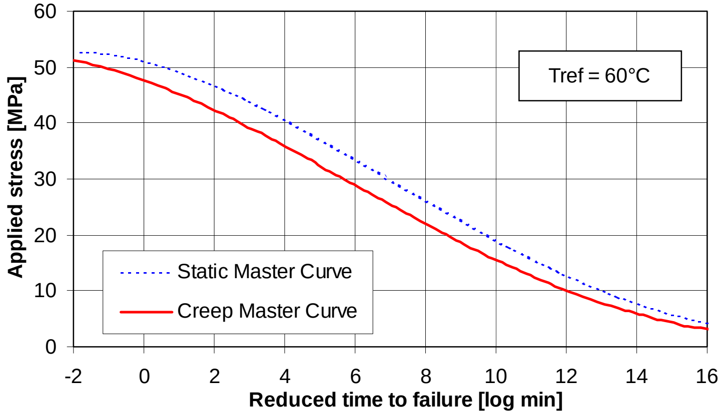
Long term creep life can be predicted from series of less time-consuming constant strain rate tests



1min 100min 1wk 2yrs 190yrs **time to failure at 60ºC**

1min 100min 1wk 2yrs 190yrs **time to failure at 80ºC**

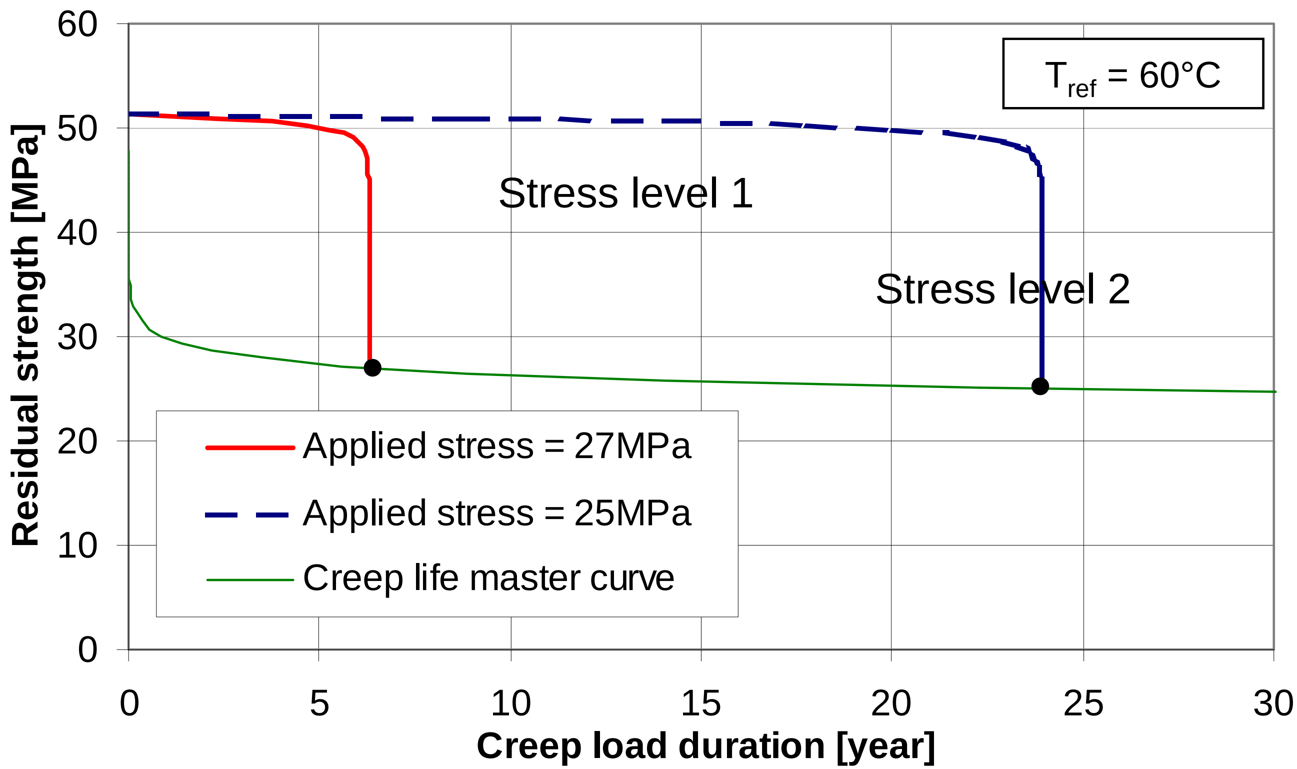
Residual Strength after Creep Loading



Master curve of static strength
Master curve of creep life

Based on linear cumulative damage law and time-dependence of strength

Residual static strength after creep loading



Conclusion

• Accelerated Testing Methodology (ATM) is the key to the long-term material characterization of composite materials

• The generated fatigue and creep master curves are applicable to wide ranges of temperature, time to failure, and loading conditions, making them ideal building blocks of material durability database.

• ATM / SIFT combination can be used to predict the durability of complex composite structures based on the durability database of the basic material properties.